Computational Approach to Color Overlapped Integral Imaging for Depth Estimation

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** Short Paper*

***Abstract*: A computational approach to depth estimations using a color over lapped integral imaging system is presented. The proposed imaging system acquires multiple color images simultaneously through a single lens with an array of multiple pinholes that are distributed around the optical axis. This paper proposes a computational model of the relationship between the real distance of an object and the disparity among different color images. The proposed model can serve as a computational basis of a single camera-based depth estimation.

***Keywords*: Depth estimation, Computational imaging system, Color overlapped integral imaging

1. Introduction

An integral imaging system processes three-dimensional (3D) optical information using multiple pinholes or an array of lenses, as shown in Fig. 1 [1].

Most work on depth estimations require multiple images, which are the same scenes with different angles of view [2]. For a depth estimation from a single image, Levin et al. used the coded aperture imaging system, which has a specially patterned mask on the aperture [3]. The Levin's method relies heavily on the specific image priors, which results in increasing noise sensitivity and distance ambiguity. The dual aperture system was proposed in 1677 [4], and various techniques using orthogonal polarizers, complementary filters, and electro-optical blocks were developed. Recently, Bae proposed a means to measure the depth from a very small lens system with a dual aperture [5]. This method, however, requires additional hardware for light integration on sensors, such as a sensor array. A new computational imaging architecture was proposed, which captures four images from the same scene with each image being taken with a different aperture settings [6]. On the other hand, this approach has a complicated optical design that includes aperture splitting mirrors and imaging lens.

The proposed method uses only a modified aperture for depth estimation without using multiple sensors or the sophisticated alignment of optical elements.

The concept of integral imaging has served as a theoretical basis for auto-stereoscopic and multi-scopic 3D systems [7].

Maik et al. proposed a depth estimation system using a single lens with multiple color filter apertures (MCAs) instead of using multiple cameras [8]. In this study, the original MCA system can be considered a color overlapped integral imaging system with an array of three pinholes. Based on this observation, this paper presents a computational model of the relationship between the real depth of an object and the disparity among relatively shifted color images.

2. Depth Estimation using a Color Overlapped Integral Imaging System

Fig. 2 shows the geometric configuration of the proposed system. As shown in Fig. 2, light rays, which are reflected by an object away from the lens by u, pass through the array of multiple pinholes covered by different color filters, and then refract them by the thin convex lens to make multiple color images on the imaging sensor.

As the pinholes are distributed around the optical axis, corresponding color images are relatively misaligned according to the distance of an object. In other words, the set of acquired color images contain complete information on the depth of an object given parameters of the optical system.

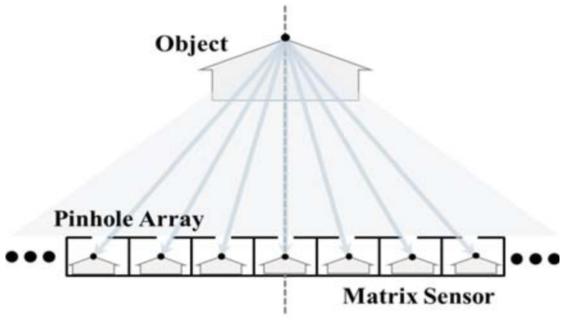


Fig. 1. Optical pickup system using a pinhole array.

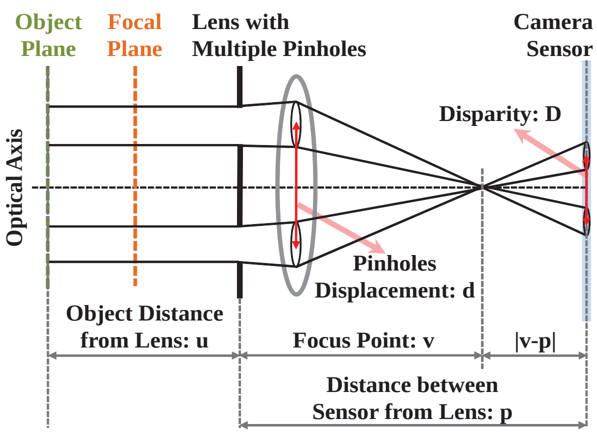


Fig. 2. Geometric configuration of the proposed color overlapped integral imaging system using multiple color filter apertures or pinholes.

Let u be the distance of an object from the lens, d is the fixed distance between pinholes, v is the focus point of the lens, p is the distance between the lens and the imaging sensor, and D is the disparity among color images acquired by the imaging sensor, all in centimeters (cm). v can be considered the focal length of the lens if u is sufficiently larger than p.

The final goal of the proposed work was to establish a mathematical model to calculate u from a given disparity, D, and the optical parameters, $\{d, v, \mathrm{p}\}$. Consider the function relating these quantities as follows:

$$u = F\left(p, d, D\right). \tag{1}$$

This study assumed that, without a loss of generality, the lateral and longitudinal magnification ratios are the same and are denoted as M. Using simple geometry, the magnification ratio is expressed as

$$M = \frac{p}{u} = \frac{D}{d}. \tag{2}$$

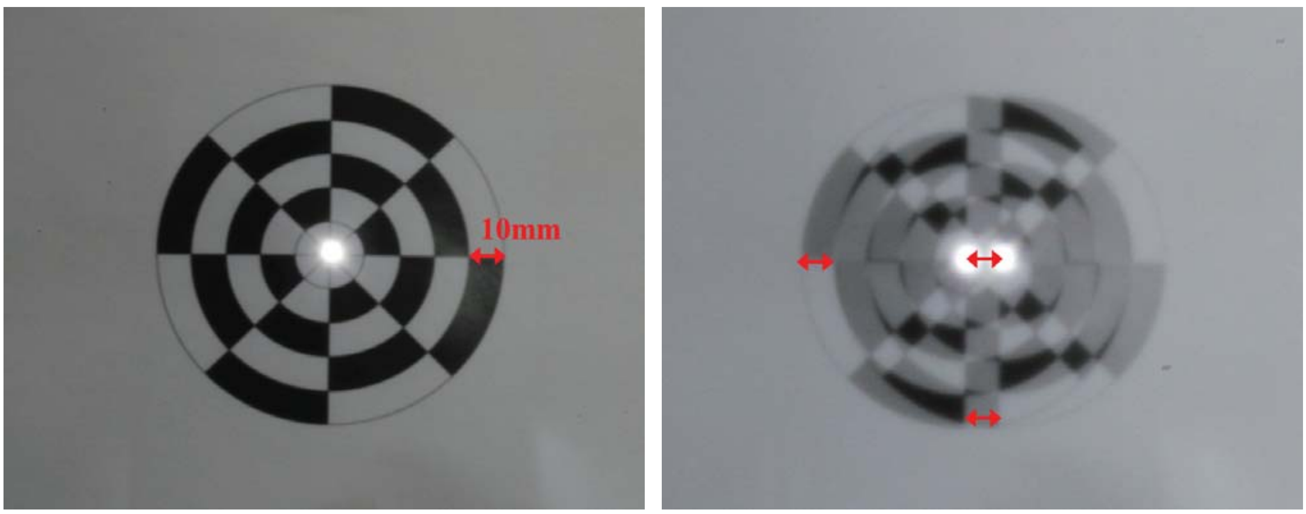
Using the property of the magnification ratio given in (2), the depth u can be expressed as

$$u = p\frac{d}{D}. \tag{3}$$

To prove that the linear model in (3) is valid, given a fixed d, D was measured using the extended set of different u and p values. The measurement model can be expressed as

$$u_k = p_i\frac{d}{D}, \tag{4}$$

where $u_k \in [200\ cm,\ 700\ cm]$, $p_i \in [v - 10\ cm,\ v + 10\ cm]$, and $d = 1\ cm$. Fig. 3 shows the input object pattern with a white light source in the center and the correspondingly



(a) (b)

Fig. 3. (a) Input object pattern with a light source in the center, (b) the overlapped image acquired using two pinholes.

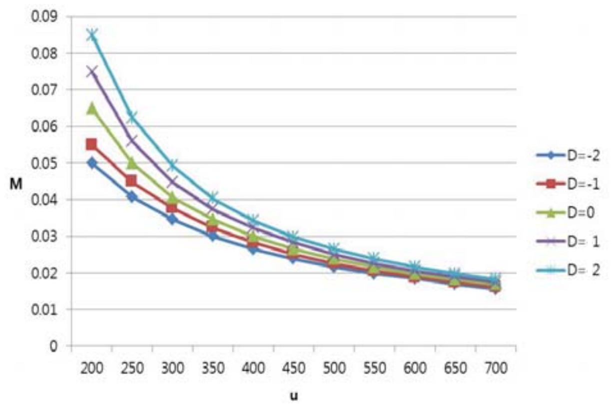


Fig. 4. Measurement of the relationship between M and u using D = -2, -1, 0, 1, and 2 cm.

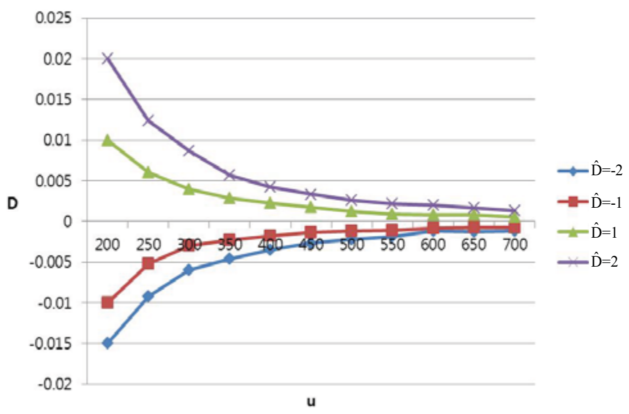


Fig. 5. Measurement of the relationship between u and $\hat{D}$ = -2, -1, 1, and 2 cm.

acquired image.

Because the pinhole diameter is sufficiently large, the light source can be considered to generate incoherent light. Fig. 4 presents the measured relationship between M and u with various D and p values. Based on the measurement given in Fig. 4, four different $\hat{D}_i = M_i - M_0$, can be calculated for $i \in \{-2,-1,1,2\}$ [cm], as shown in Fig. 5.

As shown in Fig. 6, the fitting values were derived by comparing the measured disparity, D, with the computed values of $\hat{D}_i$ given in Fig. 5.

Based on the relationship between the measured and computed disparities, as shown in Fig. 6, the computational model of the depth estimation can be established using a random sample consensus (RANSAC) algorithm [9]. Given the set of point $X = [D \quad D_i]^T$, as shown in Fig. 6, the best-fitting line $l = \theta_1 x_1 + \theta_2 x_2 + \theta_3 x_3$, can be obtained The line fitting error is determined as follows:

$$E(T_D;\theta_i) = \frac{\theta_1 x_1 + \theta_2 x_2 + \theta_3 x_3}{\sqrt{\theta_1^2 + \theta_2^2}}, \qquad (5)$$

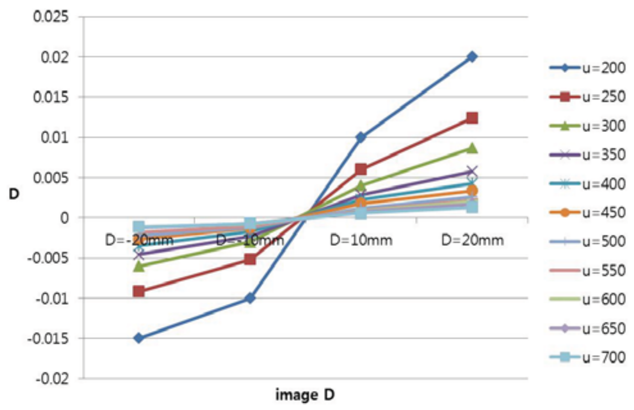


Fig. 6. Fitting results by comparing measured and computed disparities with eleven different depths.

Table 1. Specifications of the prototype MCA camera.

The MCA Camera Specifications	
Camera Type	Digital Single Lens Reflex (DSLR)
R, G, B Filters	Green-Kodak-Wratten Filter No. 58 Blue-Kodak-Wratten Filter No. 47 Red-Kodak-Wratten Filter No. 25
F-number	5.6
Sensor	$23.7 \times 15.6mm$ RGB CCD, 6.31 million total pixels
Shutter	30 to 1/4,000 sec.
Color Mode	Triple mode for R, G, and B channels

where T_D represents a distance threshold.

The proposed computational model of the color overlapped integral imaging system can be extended to the three pinhole model, where each pinhole is covered by one of red, green, and blue color filters. Fig. 7(a) shows the overlapped RGB color images acquired by the proposed system.

A special pattern image captured by the proposed MCA camera with a white light source was used to establish the computational model of the MCA-based integral imaging system.

Given the model, the real depth of an object can be estimated from the overlapped RGB color images by appropriate image processing algorithms [10]. The input image was analyzed based on the MCA color invariance model, as shown in Fig. 7(b). The model was boosted for an improved depth feature and used to extract the color-invariant features using a Harris corner detector. After extracting the depth features, the disparity was calculated and the object distance was then estimated.

Fig. 8 presents a prototype of the proposed color overlapped integral imaging camera and the configuration of the multiple color filter apertures. Table 1 lists the specifications of the color filters and the optical parameters of the system.

(a) (b)

Fig. 7. (a) Overlapped RGB color images acquired by the proposed integral imaging system, (b) a sample overlapped RGB color image with color features on which the disparity is measured.

(a) (b) (c)

Fig. 8 Prototype the MCA system: (a) front view of the lens, (b) the camera, (c) configuration of the lens assembly.

3. Conclusion

This paper presented a novel approach to estimating the object depth using a color overlapped integral imaging system. The major contribution of this work is twofold: (i) this study proved that the original MCA camera [8] can be considered as a color overlapped integral imaging system with the array of three pinholes covered by RGB color filters, and (ii) a computational model for the relationship between the real depth of an object and the disparity among relatively shifted color images was established. The proposed imaging system enables a single camera equipped with the MCA to estimate the depth of an object using an appropriate set of image processing algorithms including image segmentation, feature extraction, and registration. In addition to a depth estimation, the proposed MCA camera can be applied to multifocusing [11], image enhancement [12], and simultaneous object tracking and depth estimation [13].

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